

Performance assessment of a micro-cogeneration system under realistic operating conditions



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ARTICLE INFO

Article history:

Received 7 December 2012

Accepted 1 March 2013

Available online 2 April 2013

Keywords:

Cogeneration

Micro-cogeneration

Performance assessment

Exergy

Carbon dioxide emission

ABSTRACT

The European Parliament stated that high-efficiency cogeneration is a Community priority given the potential benefits of cogeneration with regard to saving primary energy and reducing emissions. According to this position, the performance of many micro-cogeneration systems have been assessed from an energy and environmental point of view. However, in the most part of cases, the assessments have been performed by using technical data from manufacturers and/or experimental results measured during steady-state operation, without considering the inefficiencies related to the transient periods; in addition, few works have been devoted to analyze the system operation from an exergy-based point of view.

In this paper the electric load-following operation of an internal combustion engine based micro-cogeneration unit with 6.0 kW as nominal electric output has been experimentally investigated in electric load-following operation during a 24 h dynamic test with the application of a realistic daily load profile representing the Italian domestic non-HVAC electric demand for a multi-family house of five dwellings. The measured data have been compared with those that would be associated with servicing the building with electricity from the central electric grid and heat from a natural gas fired boiler from an energy, exergy and environmental points of view.

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1. Introduction

The European Union recently established ambitious targets to increase the utilization of renewable energy up to 20%, reduce greenhouse gas emissions by at least 20%, and achieve a primary energy saving of 20% by the year 2020 in relation to reported 1990 levels [1]. Taking into account that residential applications are likely to be significant energy consumers in all the industrialized countries, the reduction of greenhouse gas emissions in the building sector to a sustainable level will require tremendous efforts to increase both energy efficiency and the share of renewable energies.

In the Directive 2004/8/EC of the European Parliament and of the Council [2] is stated that high-efficiency cogeneration (i.e. the combined production of electric power and thermal power, starting by a single primary energy source) is a Community priority given the potential benefits of cogeneration with regard to saving primary energy, avoiding network losses and reducing emissions, in particular of greenhouse gases. In addition, this Directive [2] affirms that it is therefore necessary to take measures to ensure that the cogeneration potential is better exploited.

Taking into account that cogeneration may help to improve the situation on the supply side by cutting both the non-renewable energy demand for residential buildings and peak loads in the electric grid, the study of micro-cogeneration systems (cogenerators with electric output lower than 50 kW) is gaining more and more interest in the scientific world. Many papers [3–21] assessed the MCHP unit performances and demonstrated that the micro-cogeneration technology (electric output lower than 50 kW) has the potential, if designed and operated correctly, to reduce primary energy consumption and greenhouse gas emissions. In addition, micro-cogeneration can be economically attractive, and, thanks to its distributed nature, may help to improve reliability and security of local and national electricity supply [22–24].

More and more micro-cogeneration systems appear on the market of residential heating appliances [25,26] based on different technologies of prime mover. Reciprocating internal combustion engine based cogeneration systems are usually the prime mover of choice for small scale cogeneration applications thanks to their well-proven technology, robust nature, and reliability. They are available over a wide range of sizes ranging from few kilowatts to more than several megawatts, and can be fired on a broad variety of fuels with excellent availability, making them suitable for numerous cogeneration applications in residential, commercial, institutional and small scale industrial loads.

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Nomenclature

Latin letters

AT	acquisition time
B	natural gas fired Boiler
$\bar{c}$	average specific heat (kJ/kg K)
CO ₂	carbon dioxide
CS	conventional energy system
E	energy (kW h)
Ex	exergy (kW h)
$\dot{E}x$	exergy rate (kW)
EU	European Union
f	functional relationship
f_q	quality factor
GHG	greenhouse gas
h	specific enthalpy (kJ/kg)
HVAC	heating ventilation air-conditioning systems
LHV	lower heating value (kJ/kg)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
MCHP	Micro Combined Heat and Power
P	power (kW)
PP	Power Plant
RAI	Relative Avoided Irreversibility
s	specific entropy (kJ/kgK)
T	temperature (°C)
T_0	dead-state or environment temperature (K)
TCO ₂ ER	cogeneration CO ₂ emission reduction
u	uncertainty
$\dot{V}$	volumetric flow rate (Nm ³ /s)
w	generic pollutant
x	measured value of generic parameter
X	generic parameter
Y	generic measurand

Greeks

χ	molar fraction
Δ	difference
μ	emission factor (kg/kW h)
η	efficiency
ρ	density (kg/m ³)

Superscripts

E	energy
el	electric
p	primary
th	thermal

Subscripts

B	natural gas fired Boiler
cw	cooling water
CO ₂	carbon dioxide
CS	conventional energy system
Demand	end-user request
el	electric
E	energy
Ex	exergy
fuel	natural gas
gross	related to the fuel consumption
i	i^{th}
in	inlet
MCHP	Micro Combined Heat and Power
out	outlet
p	primary
PP	Power Plant
th	thermal

One of the key questions that has to be answered prior to the decision to invest in a MCHP (Micro Combined Heat and Power) unit is the performance of the system in comparison to alternative systems. Today available micro-cogeneration systems already reach a very high total efficiency of more than 90% with respect to output of electricity and heat and compared to the input of fuel. However these high values are often measured under stationary operation with nominal conditions. In real life heat and electricity demand is not constant, but it varies due to user requirements. So under real conditions, as they appear in residential buildings, MCHP units does not operate in steady-state regime; more generally they frequently passes through transient periods, especially during start-up or shut-down of the system. This has a negative influence on the efficiency of the system. In several papers [3–9] the MCHP unit performance have been assessed by using technical data from manufacturers and/or experimental values of system efficiency related to steady-state operation; this approach does not allow taking into account the inefficiencies of the unit during transient operation and, therefore, it is insufficient to make statements about practical suitability of MCHP systems. The small cogeneration units cannot be assessed without overall examination of their efficiency as applied to the thermal and electrical demand profiles of a practical application.

As a consequence, only field trials under electric/thermal load profiles representative of real end-users with statistically meaningful sets of data can give a proper understanding and prediction of how efficient these technologies are [10–12,21]. As alternative, the performances of MCHP units can be assessed by following simulation approaches that use dynamic building and unit models able to closely reproduce the real system operation under different operat-

ing scenarios. Compared to bench/field experiments that are expensive and time consuming, the simulation approach allows exploring a wide variety of operating scenarios [13–18], even if this approach is only able to partially reproduce the real system operation with an accuracy depending on the accuracy of the models of the systems components.

An AISIN SEIKI reciprocating internal combustion engine based micro-cogeneration device fuelled by natural gas [27] is installed at the Built Environment Control Laboratory of Seconda Università degli Studi di Napoli. The unit is able to realize part load operation by reducing the turning speed of the generator with 6.0 kW as nominal electrical output and 11.7 kW as nominal thermal output. Our research group [4] investigated experimentally the possibility of utilization of the same small cogeneration unit by evaluating its energy, economic and environmental impact implications in comparison to Conventional Systems for separate production of heat and electricity. Encouraging results have been obtained: in fact the assessment showed that AISIN SEIKI system operation potentially allows for a significant reduction of both primary energy consumption and carbon dioxide emissions. However the analysis has been performed by considering experimental data achieved during steady-state operation in electric load-following logic at different electric output levels. The performance of the unit has not been investigated by considering its application in conjunction with a real electrical demand profile.

In order to get a more detailed and accurate indication on the suitability of the AISIN SEIKI unit to supply heat and electricity to a building, its performance has been measured during a dynamic test with a duration of 24 h. The system has been operated in

electric load-following logic by applying a realistic daily electric load profile derived by the electric load profile suggested by Sasso et al. [28] representing the Italian domestic non-HVAC electric demand for a multi-family house of five dwellings. This profile is based on 10-min measurements onsite of the electric consumptions during cold season of 110 flats located in six Italian regions analyzed for 3 years within the SAVE EURECO and MICENE projects [29]. The measured performances of MCHP unit have been compared with those that would be associated with servicing the building with electricity from the central electric grid and heat from a natural gas fired boiler in order to estimate the suitability of the investigated unit in comparison to Conventional Systems based on separate energy production. The most part of the scientific works assess the micro-cogeneration suitability based on the first law of thermodynamics. This law states that energy is conserved in every device or process; however, the energy conservation idea alone is inadequate for depicting some important aspects of resource utilization due to the fact that it considers heat and work as commodities with the same quality: a comprehensive analysis of a thermodynamic system should include both energy and exergy analyses in order to obtain a more complete picture of system behavior. In fact the exergy analysis is a method that uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics and it is gaining increasingly widespread acceptance as a useful tool in the design, optimization and improvement of energy systems [32,33]. There is a lack of exergy-based performance analysis [8–9,17], especially for MCHP systems based on internal combustion engine systems. So the measured AISNI SEIKI unit performance has been assessed not only based on the first law of thermodynamics, but also from the second law of thermodynamics point of view. The measured data have been considered not only from an energy and exergy points of view, but also for evaluating the carbon dioxide emissions related to MCHP system operation.

The energy, exergy and environmental analyses have been performed for several efficiency values of the reference Conventional System based on separate electric and thermal energy production, by considering the most meaningful indexes suggested in literature. The proposed methodology can be applied to other types of cogeneration systems.

2. Experimental set-up

A schematic diagram of the test apparatus installed at the Built Environment Control Laboratory of Seconda Università degli Studi di Napoli detailing instrumentation components is shown in Fig. 1. The experimental set up is located in Frignano, a municipality in the Province of Caserta (around 20 km far from Naples).

The micro-cogeneration device is the model GECC60A2 NR/P produced by AISIN SEIKI [27]. This model is based on a natural gas fuelled reciprocating internal combustion engine with three cylinders, four strokes and a total displacement of 952 cm³. The unit has a rated electric output of 6.0 kW, and a nominal thermal output of 11.7 kW. The thermal recovery during MCHP operation is obtained from the exhaust gases and the engine jacket of the micro-cogenerator by using a water-glycol mixture as coolant. The heat recovered by the water-glycol mixture is transferred to the cooling water flowing in a plate heat exchanger located inside the unit. The cooling water is circulated by the wet rotor pump P1 and its mass flow rate can be modified by varying the pump revolution speed: three different values can be manually set. The recovered thermal power is stored in an internal heat exchanger equipped 1000 dm³ tank. The hot water storage is insulated with 50 mm flexible polyurethane layer and is furthermore equipped with an auxiliary 4.0 kW electric resistance that can be fed by the micro-cogenerator. During the winter the thermal energy stored is used for heating a part of the entire building: the hot water in the storage tank is circulated into three fan-coils by using the wet rotor pump P2.

In the following additional detail about AISIN SEIKI unit operation are provided. In particular it can be noticed that the cogeneration device can operate in electric load-following logic or, as alternative, in thermal load-following logic.

In case of electric load-following operation, the cogeneration device modulates its electric output according to the electric load required by the end-user. In the lab the electric demand profile can be varied by using eight halogen lamps; each lamp is equipped with a timer by means of which it is possible to schedule the switching on and the switching off of each lamp. As alternative, the micro-cogenerator can be operated in order to follow the electric needs of the building for lighting and the operation of PCs, printers, plotters, etc. In this configuration, the unit is connected

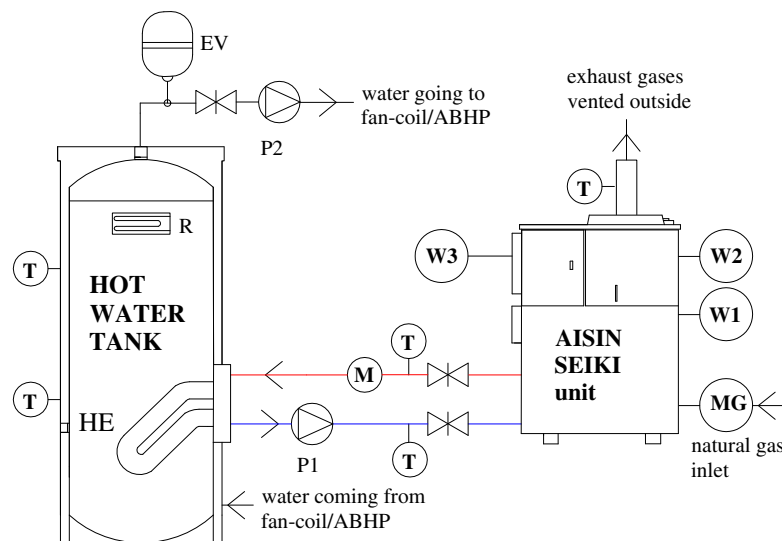


Fig. 1. Scheme of experimental apparatus (T: resistance thermometer; M: cooling water volumetric flow meter; W: Wattmeter; MG: natural gas volumetric flow meter; P: variable speed driven Pump; HE: internal Heat Exchanger; EV: Expansion Vessel; R: electric Resistance; ABHP: Absorption Heat Pump).

in parallel to the electric grid. The unit is able to start only when the electric load is higher than about 300 W.

As alternative to the electric load-following operation, the unit can operate according to an external temperature signal coming from a thermostat located on the recovery tank: when this temperature is lower than the set-point value, the unit operates providing its maximum electric output; when the water temperature in the storage exceeds the set-point value, the unit switches in standby mode operation.

During both electric load-following operation and thermal load-following operation, AISIN SEIKI unit exhibits four different operating modes with markedly different characteristics [34,35]:

- standby;
- warm-up;
- normal mode;
- cool-down.

Standby is the system mode operation when no electric or thermal output is requested; during standby operation the unit generates no heat and consumes no fuel, but the electronic controllers within the unit require some electricity while awaiting activation. Warm-up is the period during which there is a static time delay between activation of the unit and electrical power generation; during warm-up operation some electric power is consumed. During normal mode operation the MCHP system produces both thermal and electric power by consuming some fuel. Cool-down occurs just after normal mode operation, starting when the fuel supply has stopped and finishing when standby mode is entered; during cool-down, some heat is recovered, even if fuel consumption is not zero; some electricity is also required by the auxiliary electrical systems to complete the shutdown and no electric power is provided to the end-user.

The above-mentioned four modes of operation are not only inherent for the AISIN SEIKI unit, but they general also for other types of micro cogeneration systems. As stated previously, system efficiency during steady-state operation is completely different from that one observed during the other operating phase: therefore, taking into account the system operation during standby, warm-up and cool-down in assessing the performance of the unit is mandatory.

The experimental plant is well instrumented in order to measure directly the following parameters:

- water temperature at inlet and outlet of MCHP system, water temperature within the tank;
- exhaust gases temperature;
- water mass flow rate going from MCHP system towards the storage;
- natural gas mass flow rate entering the micro-cogenerator;
- electric load applied to the MCHP system;
- electric power supplied by the grid to the MCHP system;
- electric power supplied by the MCHP system to the end-user.

Water and exhaust gas temperatures are measured by using resistance thermometers Pt100; water mass flow rate is obtained by using an ultrasonic mass flow sensor, while a thermal mass flow meter is installed to evaluate the natural gas volumetric flow rate; three watt-meters measure the electric power entering and exiting the unit.

The parameters directly measured during the experiments and the instrumentation employed are specified in Table 1. The operating range and the uncertainty associated to each instrument are also given in Table 1.

Table 1
Main characteristics of the plant instrumentation.

Parameter	Instrument	Operating range	Uncertainty
T	Resistance thermometer Pt100	–50–100 °C	±0.2 °C
$\dot{V}_{cw}$	Ultrasonic volumetric flow meter	0–50 l/min	±2.5% of full scale
$\dot{V}_{fuel}$	Thermal volumetric flow meter	0–5.0 N m ³ /h	±0.8% of reading ±0.2% of full scale
$P_{el,MCHP,out}$ $P_{el,MCHP,in}$	Wattmeter	0–6 kW	0.2% of full scale
$P_{el,demand}$	Wattmeter	0–10 kW	0.2% of full scale

The signals coming from the resistance thermometers Pt100 are acquired by three cFP-RTD-124 analog input modules (produced by National Instruments®), while the signals coming from the other sensors are managed by two cFP-AI-110 analog input modules (produced by National Instruments®). Each acquisition device is a 16-bit resolution system with eight current outputs (4–20 mA). The digital data coming from the modules are sent to a personal computer. The software LabView 8.2 is used for both defining the acquisition frequency and recording all parameters.

In addition to the instruments installed by the authors, the micro-cogeneration device's commissioning software GECMON allows recording additional intrusive measurements including temperature of water–glycol mixture exiting and entering engine, ambient temperature, engine revolution speed, etc.

3. Measurement procedure and uncertainty

When reporting the result of a measurement of a physical quantity, a quantitative indication of measurement uncertainty should be given so that those who use it can assess its reliability. Without such an indication, measurement results cannot be compared, either among themselves or with reference values given in a specification or standard.

In this paper the uncertainty associated to the measured flows of primary power, thermal power and electric power entering or exiting the MCHP system are evaluated according to the procedure suggested by the Guide to the expression of Uncertainty in Measurement [36]. According to [36], the uncertainty u associated to a measurand Y that depends upon a number of input quantities $X_1, \dots, X_N$ can be performed by using the following formula:

$$u(y) = \sqrt{\sum_{i=1}^N (\partial f / \partial x_i)^2 \cdot u^2(x_i)} \quad (1)$$

where f is the functional relationship between Y and $X_1, \dots, X_N$ and y an estimation of the measurand Y obtained by substituting the measured values $x_1, \dots, x_N$ of the parameters $X_1, \dots, X_N$ in Eq. (1).

The electric power $P_{el,MCHP,out}$ supplied by the micro-cogeneration unit to the end-user is directly measured through a wattmeter. Based on the manufacturer calibration certificate, in the following an uncertainty value of 0.2% of full scale (Table 1) is used for evaluating its uncertainty.

As stated above, during standby, warm-up and cool-down the MCHP system does not provide electricity to the end-user, but it requires some electric power from the grid due to the operation of electronic controllers and auxiliary electrical systems within the unit. The electric power $P_{el,MCHP,in}$ supplied by the grid to the MCHP system is directly measured by means of a wattmeter with the same characteristics of that one used to measure $P_{el,MCHP,out}$ (Table 1).

The primary power input $P_{p,MCHP}$ is evaluated as the sum of two terms: the first one is the product of the mass flow rate $\dot{m}_{fuel}$ of the fuel (i.e. natural gas) and the lower heating value of the fuel LHV_{fuel} , while the second one is the electric power $P_{el,MCHP,in}$ supplied by the grid to the MCHP system:

$$P_{p,MCHP} = \dot{m}_{fuel} \cdot LHV_{fuel} + P_{el,MCHP,in} = P_{gross,MCHP,in} + P_{el,MCHP,in} \quad (2)$$

During normal mode operation electric power is provided to the end-user: as a consequence, it results $P_{el,MCHP,in} = 0$ and

$$P_{p,MCHP} = \dot{m}_{fuel} \cdot LHV_{fuel} = P_{gross,MCHP,in}$$

The fuel mass flow rate is obtained by the product of volumetric flow rate and the natural gas density at measurement condition:

$$\dot{m}_{fuel} = \dot{V}_{fuel} \cdot \rho_{fuel} \quad (3)$$

As a consequence, the relative uncertainty of $P_{p,MCHP}$ can be calculated as follows by applying the propagation of uncertainties [36]:

$$u(P_{p,MCHP})/P_{p,MCHP} = \sqrt{u^2(\dot{V}_{fuel})/\dot{V}_{fuel}^2 + u^2(\rho_{fuel})/\rho_{fuel}^2 + u^2(LHV_{fuel})/LHV_{fuel}^2 + u^2(P_{el,MCHP,in})/P_{p,MCHP}^2} \quad (4)$$

Fuel volumetric flow rate measurement is carried out by means of a thermal mass flow meter with an uncertainty rated by manufacturer equal to $\pm 0.8\%$ of reading $\pm 0.2\%$ of full scale (Table 1).

The accuracy in density measurement depends mainly on uncertainty related to mixture composition [37]; the estimated value is typically around $\pm(0.10\text{--}0.50)\%$ of reading [38]; in the following an uncertainty value equal to $\pm 0.10\%$ of the density measurement is assumed.

The lower heating value is defined as follows:

$$LHV_{fuel} = \sum_i \chi_i \cdot LHV_i \quad (5)$$

where χ_i is the molar fraction of i^{th} component and LHV_i is the heating value of i^{th} component. The main factors of uncertainty on LHV_{fuel} depend on instrumental uncertainties and the mixture composition and on the lag composition settings. The lower heating value is usually measured indirectly, by manually setting up a gas mixture composition that is not referred to a single final user of the natural gas grid, but is calculated for a macro-zone of the grid as a whole, typically on a monthly base. In this case, that is by far much frequent for small and medium cogeneration, the value of LHV_{fuel} is usually provided by the local gas utility, and the extended relative uncertainty for the lower heating value is obviously great. Our lab is not equipped with an instrument for measuring the natural gas composition: as a consequence, in the following a relative uncertainty value equal to 5.0% is assumed, according to what is reported in [38–40].

The thermal power $P_{th,MCHP}$ recovered from MCHP unit is the product of the cooling water mass flow rate and the enthalpy difference between the inlet and the outlet of the closed cooling water loop:

$$P_{th,MCHP} = \dot{m}_{cw} \cdot \Delta h_{cw} = \dot{m}_{cw} \cdot (h_{cw,out} - h_{cw,in}) \\ = \dot{V}_{cw} \cdot \rho_{cw} \cdot (h_{cw,out} - h_{cw,in}) \quad (6)$$

Therefore the thermal power uncertainty can be calculated as follows:

$$u(P_{th,MCHP})/P_{th,MCHP} = \sqrt{u^2(\dot{V}_{cw})/\dot{V}_{cw}^2 + u^2(\rho_{cw})/\rho_{cw}^2 + u^2(\Delta h_{cw})/\Delta h_{cw}^2} \quad (7)$$

The cooling water volumetric flow rate is measured by an ultrasonic volumetric flow meter characterized by an uncertainty equal to 2.5% of full scale (Table 1).

The uncertainty of enthalpy difference is evaluated by taking into account that:

$$(h_{cw,out} - h_{cw,in}) \approx \bar{c}_{cw} \cdot \Delta T_{cw} = \bar{c}_{cw} \cdot (T_{cw,out} - T_{cw,in}) \quad (8)$$

where $\bar{c}_{cw}$ is the average cooling water specific heat. By applying the law of propagation of uncertainty given in [36], it can be derived that:

$$u(\Delta h_{cw})/\Delta h_{cw} = \sqrt{u^2(\bar{c}_{cw})/\bar{c}_{cw}^2 + u^2(\Delta T_{cw})/\Delta T_{cw}^2} \quad (9)$$

The uncertainty of temperature difference depends on the type of thermometer; in particular, when the temperature difference is evaluated as the difference of two temperature measures, the

relative uncertainty may reach very high values. In fact $u_c(\Delta T_{cw})$ should be calculated as follows:

$$u(\Delta T_{cw}) = \sqrt{u^2(T_{cw,out}) + u^2(T_{cw,in})} \quad (10)$$

In this paper the uncertainty associated to both $\bar{c}_{cw}$ and ρ_{cw} is neglected.

4. Experimental results

An European Project, called “SAVE Eureco” [29], has been performed with the main aim to evaluate the electricity uses in the residential sector of 5 European countries (Italy, Greece, Denmark, France, Portugal) in order to producing reference information on a European scale that will allow all the research teams, and all the organizations that work in the modeling and forecasting of electrical consumptions, to base their works on reliable data and on sane basis.

A report published by the Politecnico of Milano shows the measurements onsite of the electric energy consumptions in the Italian residential sector carried out within the SAVE Eureco project [29]. The data described in this report are referred to 110 flats (located in six different Italian regions) characterized by an average surface area of 106 m², a number of occupants ranging between 2 (9% of cases) and 5 (14% of cases) and by an average annual electric energy consumption equal to 3229 kWh. The electric energy consumptions related to standby operation, electric water heaters, power supply for gas boilers, cold domestic appliances, lighting systems, laundry, dish-washing and cleaning appliances, personal computers and audiovisual appliances have been recorded every 10 min during a 3 years span of time (from 2000 to 2002). According to the onsite measurements reported in [29], Sasso et al. [28] derived a daily Italian domestic electrical non-HVAC demand profile during cold season for a Single Family House (SFH) located in the south of Italy with 120 m² as usable floor area. Superposition of several SFH profiles provides the 5-dwellings multi-family house electric load profile depicted in Fig. 2 (dashed red¹ line).

¹ For interpretation of color in Figs. 2 and 3, the reader is referred to the web version of this article.

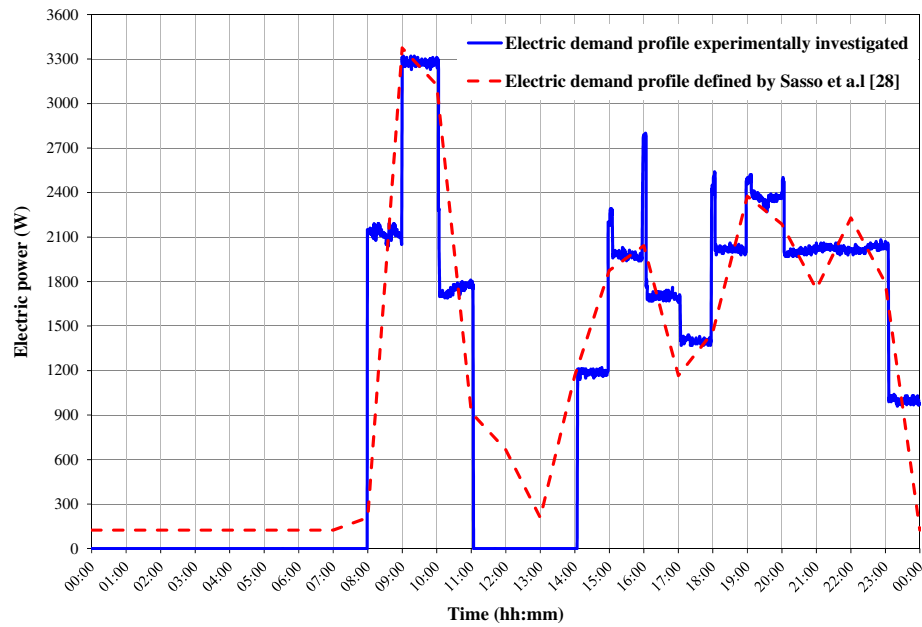


Fig. 2. Electric demand profiles.

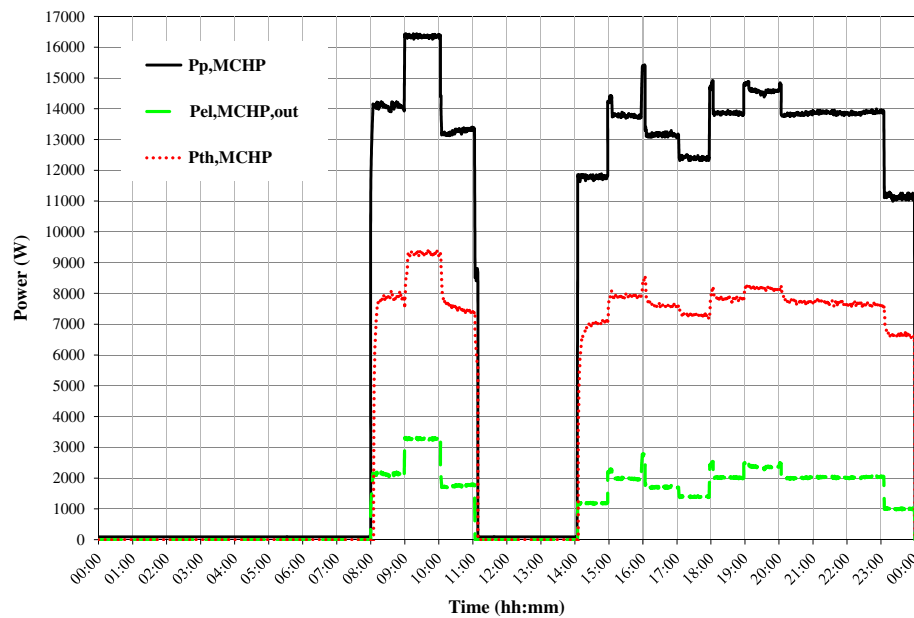


Fig. 3. Experimental values of $P_{p,MCHP}$, $P_{el,MCHP,out}$ and $P_{th,MCHP}$ as a function of the time.

In order to assess the performance of the MCHP system described in Section 3, the unit has been operated in electric demand following logic by applying an electric load as much as possible close to the electric profile indicated in Fig. 2 by the dashed red line [28]. The daily electric load profile indicated by the solid blue line in Fig. 2 has been actually applied to the MCHP unit during the experiment. The difference between the dashed red line (electric load suggested in [28]) and the solid blue line (actual electric load applied to the MCHP unit) is basically due to the fact that at our lab the electric load applied to the MCHP unit (solid blue line) is defined by managing the operation of the eight halogen lamps characterized by different nominal electric power: as a consequence, it has not been really

possible to rigorously follow the electric profile indicated by the dashed red line [28]. Even if the electric load indicated by the dashed red line in Fig. 2 is never zero during the day, the electric load actually applied to the cogeneration device (solid blue line in Fig. 2) is null during a portion of day because the MCHP unit under investigation is able to provide a net electric output to the end-user only in case of the electric load is larger than a minimum value (equal to about 500 W).

The electric profile actually applied to cogeneration device in this paper is characterized by variations in time around stepwise levels. As known, the electric load usually contains high-frequency fluctuations due to use of appliances, lights and so on; however electric load profiles with trend very similar to the one considered

in this paper have been suggested also in several other published works for a 10-flats apartment [30,31].

In Fig. 3 the primary power $P_{p,MCHP}$ consumed by the unit (black line), the electric output $P_{el,MCHP,out}$ of the MCHP system (dashed green line), and the thermal power $P_{th,MCHP}$ recovered from the exhaust gases and the engine jacket of the micro-cogenerator (dotted red line) are reported as a function of the time. The values reported in this figure represent the AISIN SEIKI unit operation under conditions as they could occur in the residential sector in case of electric load-following operation. So these values are valuable to assess the MCHP unit performance thanks to the fact that they allow to take into consideration also the system operation during transient periods.

Maximum values of $P_{p,MCHP}$, $P_{th,MCHP}$ and $P_{el,MCHP,out}$ specified in Fig. 3 are, respectively, 16436.6 W, 9398.1 W and 3320.0 W. The values of $P_{p,MCHP}$ have been calculated through Eq. (2), by assuming $\rho_{fuel} = 0.719 \text{ kg/m}^3$ [34,35] and $LHV_{fuel} = 49599 \text{ kJ/kg}$ according to the natural gas composition suggested in [41]; Eq. (6) has been used to compute the values of $P_{th,MCHP}$ with $\bar{c}_{cw} = 4.187 \text{ kJ/kgK}$ and $\rho_{cw} = 1000 \text{ kg/m}^3$, while $P_{el,MCHP,out}$ has been directly measured. As stated above, the MCHP unit consumes some electricity during standby, warm-up and cool-down operation. The electric power $P_{el,MCHP,in}$ supplied by the grid during the experiment ranges between 90 W (standby and warm-up) and 190 W (cool-down). Each parameter reported in Fig. 3 has been measured and logged every 30 s.

According to the procedure described in Section 3, the uncertainty associated to the values of $P_{el,MCHP,out}$, $P_{th,MCHP}$ and $P_{p,MCHP}$ has been estimated: both minimum and maximum value of uncertainties derived in the operating conditions investigated in this study are reported in Table 2. As can be derive from Table 2, uncertainty ranges between 7.2% and 9.8% for the thermal power, while it varies from 0.4% to 1.3% for the electric output. The maximum uncertainty in the evaluation of primary power (13.3%) is reached while the system is not operating in steady state mode; during steady-state operation $u(P_{p,MCHP})$ is nearly constant and equal to about 5%.

According to the values of power reported in Fig. 3, the values of the cumulative primary energy $E_{p,MCHP}$ consumed by the MCHP system during the entire test (that is the sum of the daily energy $E_{gross,MCHP,in}$ associated to the fuel consumption and the daily energy $E_{el,MCHP,in}$ related to the electricity supplied by the grid to the unit during standby, warm-up and cool-down operation), the cumulative electric energy $E_{el,MCHP,out}$ supplied by the MCHP system to the end-user during the test and the cumulative thermal energy $E_{th,MCHP}$ recovered from the MCHP system during the test have been calculated:

- $E_{p,MCHP} = 177.9 \text{ kW h}$;
- $E_{gross,MCHP,out} = 176.9 \text{ kW h}$;
- $E_{el,MCHP,in} = 1.0 \text{ kW h}$;
- $E_{el,MCHP,out} = 25.2 \text{ kW h}$;
- $E_{th,MCHP} = 99.9 \text{ kW h}$.

Table 2
Minimum and maximum uncertainties in the investigated experimental conditions.

	Uncertainty			
	Minimum (%)	Maximum (%)	Minimum (W)	Maximum (W)
$P_{el,MCHP,out}$	0.4	1.3	12.0	12.0
$P_{th,MCHP}$	7.2	9.8	502.2	757.5
$P_{p,MCHP}$	5.2	13.3	12.0	853.8

Fig. 4 shows the time-varying evolution of the electrical efficiency (defined as the ratio between $P_{el,MCHP,out}$ and $P_{p,MCHP}$) and thermal efficiency (defined as the ratio between $P_{th,MCHP}$ and $P_{p,MCHP}$) measured during the test. As can be derived from this figure, both electrical and thermal efficiencies are strongly dependent from the electric output of the unit. In particular, the experimental data show that the thermal efficiency increases (up to about 60%) at decreasing the electric output, while the electric efficiency rises (reaching a maximum value of about 20%) with increasing the electrical power.

These data measured during the 24 h experiment have been used in the following for assessing the performance of the AISIN SEIKI unit in comparison to a Conventional System (CS) based on separate electric and thermal energy production (composed by the national electric grid supplied through a Power Plant and a natural gas fired boiler). The assessment has been performed from an energy, exergy and environmental point of view. Taking into account that there is no definitive basis for the selection of a reference system that is accepted by all and there is no empirical solution or way to prove which reference system is best, the assessment has been performed for various efficiencies values of both Power Plant (PP) and gas fired Boiler (B). As known, a boiler is characterized by a transient behavior: in this paper its transition period has been considered as negligible and it is not taken into account in the estimation of the Conventional System performance.

5. Energy and exergy-based analysis

In order to compare the MCHP device and the Conventional System from an energy point of view, the following indicator ΔP_p is adopted:

$$\Delta P_p = (P_{p,CS} - P_{p,MCHP}) / P_{p,MCHP} \quad (11)$$

where $P_{p,CS}$ is the primary power consumed by the Conventional System for supplying the same output ($P_{el,MCHP,out} + P_{th,MCHP}$) of the MCHP unit. The values of $P_{p,CS}$ can be computed as reported below:

$$P_{p,CS} = P_{el,MCHP,out} / \eta_{PP,CS} + P_{th,MCHP} / \eta_{B,CS} \quad (12)$$

where $\eta_{PP,CS}$ and $\eta_{B,CS}$ represent the Power Plant (PP) efficiency and the Boiler (B) efficiency, respectively. In the analysis the electric power consumed during boiler operation is neglected.

Concerning the reference efficiency values, figures of $\eta_{PP,CS} = 0.461$ (about the Power Plant average efficiency in Italy, including line losses [42]) and $\eta_{B,CS} = 0.85$ (average natural gas fired boiler efficiency) could be adopted for evaluating the performance of Conventional System.

A positive value of ΔP_p indicates that the MCHP system allows for a primary power saving in comparison to the Conventional System.

Fig. 5 shows the values of ΔP_p calculated by using Eqs. (11) and (12) according to the above-mentioned figures of $\eta_{PP,CS}$ and $\eta_{B,CS}$; the values of $P_{p,MCHP}$ and $P_{p,CS}$ are also reported on the right-hand y axis of the same figure.

As can be derived from Fig. 5, AISIN SEIKI unit allows for an energy saving ($\Delta P_p > 0$) only while an electric power higher than around 2.3 kW is supplied to the end-user; maximum value of ΔP_p is around 11.1%.

Values of ΔP_p plotted in Fig. 5 have been calculated according to the values of instantaneous powers reported in Fig. 3; however the primary energy saving indicator could be also defined in terms of cumulative energies produced or consumed during the entire experiment by the unit:

$$\Delta E_p = (E_{p,CS} - E_{p,MCHP}) / E_{p,MCHP} \cdot 100 \quad (13)$$

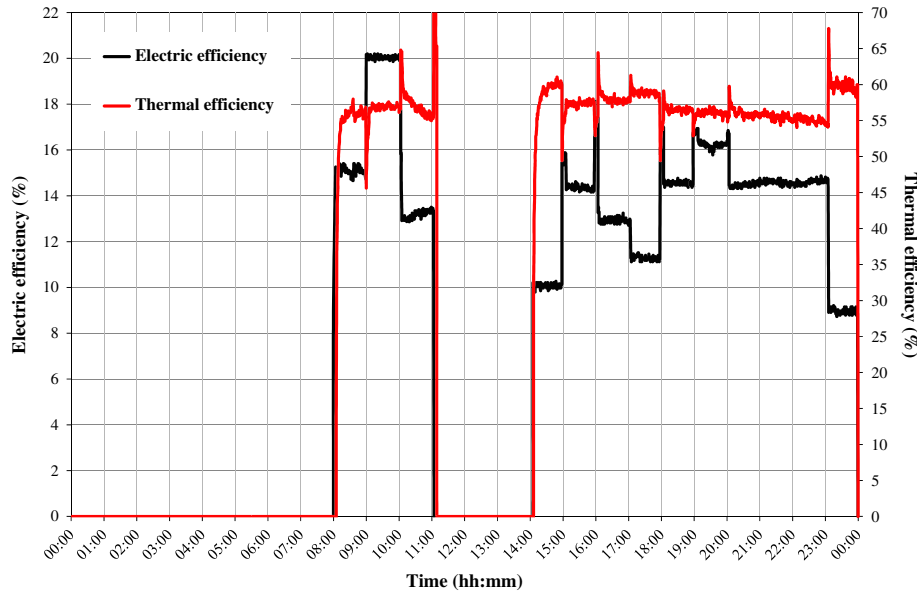


Fig. 4. Electric and thermal efficiencies as a function of the time.

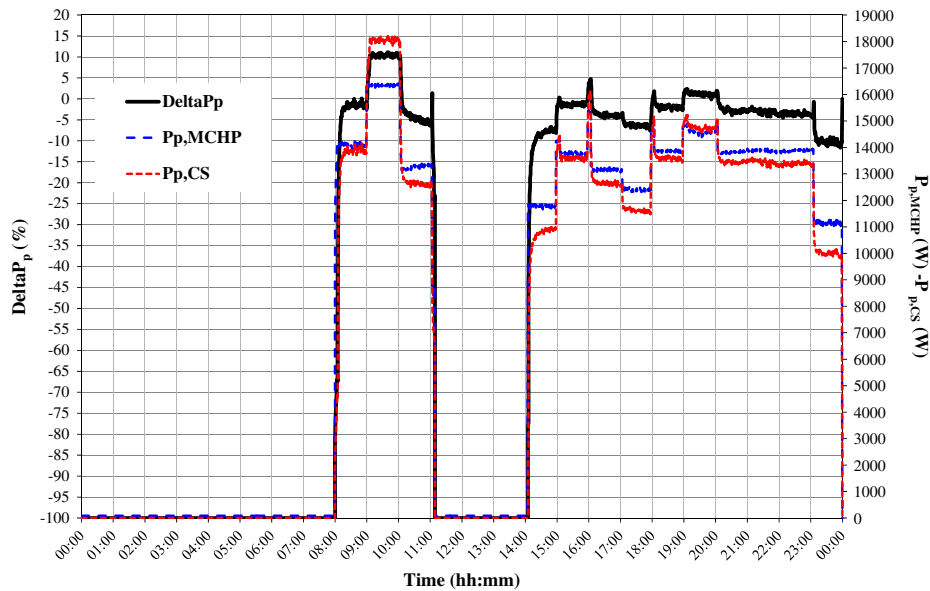


Fig. 5. Values of ΔP_p , $P_{p,MCHP}$ and $P_{p,CS}$ as a function of the time.

where $E_{p,MCHP} = 177.9 \text{ kW h}$ is the primary energy consumed by MCHP system during the entire test and $E_{p,CS}$ is the primary energy consumed by the Conventional System for supplying the same energy output ($E_{el,MCHP,out} + E_{th,MCHP} = 25.2 \text{ kW h} + 99.9 \text{ kW h}$) of the cogeneration unit. The values of $E_{p,CS}$ can be calculated as reported below:

$$E_{p,CS} = E_{el,MCHP,out}/\eta_{PP,CS} + E_{th,MCHP}/\eta_{B,CS} \quad (14)$$

As for ΔP_p indicator, a positive value of ΔE_p indicates that the MCHP system allows for a primary energy saving in comparison to the Conventional System.

In Fig. 6 the values of ΔE_p calculated by means of Eqs. (13) and (14) are plotted as a function of both Power Plant efficiency and boiler efficiency, with $\eta_{PP,CS}$ ranging between 30% and 60% and $\eta_{B,CS}$ ranging from 80% to 105%.

With respect to the thermal efficiency, based on LHV of the fuel, the range 85–105% has been considered in order to take into account the performance of a gas-fired condensing boiler.

Fig. 6 shows that, in the operating conditions investigated in this paper, the energy saving increases with decreasing both $\eta_{PP,CS}$ and $\eta_{B,CS}$. It results that, whatever is the value of $\eta_{B,CS}$, the figure of ΔE_p reduces of about 23% when $\eta_{PP,CS}$ decreases from 60% to 30%; on the other hand, whatever is the value of $\eta_{PP,CS}$, the figure of ΔE_p reduces of about 17% when $\eta_{B,CS}$ decreases from 105% to 80%. The maximum value of ΔE_p is around +17%, which is achieved when $\eta_{PP,CS} = 30\%$ and $\eta_{B,CS} = 80\%$. In addition it can be derived that the increment of ΔE_p due to an improvement of Power Plant efficiency equal to 5% decreases at increasing the starting value of $\eta_{PP,CS}$, ranging between 6.8% (case of $\eta_{PP,CS}$ increasing from 30% to 35%) and 2.1% (case of $\eta_{PP,CS}$ increasing from 55% to 60%); this is true whatever is the value of $\eta_{B,CS}$; in the same way, it can be observed that, whatever

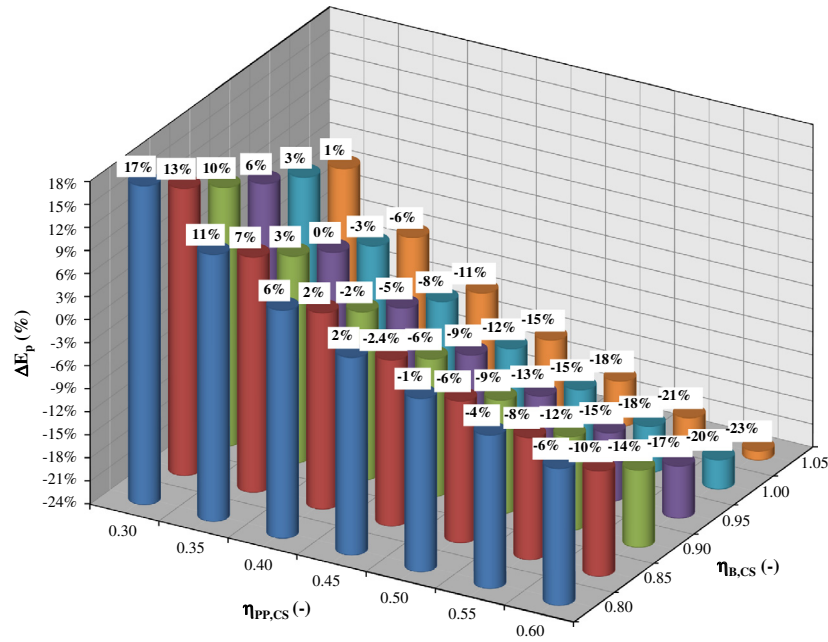


Fig. 6. Values of ΔE_p as a function of $\eta_{PP,CS}$ and $\eta_{B,CS}$.

is the value of $\eta_{PP,CS}$, the increment of ΔE_p due to an improvement of boiler efficiency equal to 5% decreases at increasing the starting value of $\eta_{B,CS}$, ranging from 4.1% (case of $\eta_{B,CS}$ increasing from 80% to 85%) to 2.7% (case of $\eta_{B,CS}$ increasing from 100% to 105%).

If the Power Plant efficiency is 46.1% (Italian context [42]) and the boiler efficiency is 85% (average boiler efficiency) the value of ΔE_p results about -3.2%; as a consequence, the Conventional System allows for a little reduction of primary energy consumption in comparison to MCHP system operation in case of $\eta_{PP,CS} = 46.1\%$ and $\eta_{B,CS} = 85\%$.

The above-mentioned results have been obtained based on the first law of thermodynamics; cogeneration plants are normally examined using energy analysis but, as pointed out previously, a better understanding is attained when a more complete thermodynamic view is taken, which uses the second law of thermodynamics in conjunction with energy analysis via exergy methods [8–9,17,32,33]. Exergy analysis helps in determining the true magnitudes of losses and their causes and locations, and improve the overall system and its components.

For a cogeneration system producing electricity and heat, the exergy efficiency or second law efficiency can be defined as the ratio between the total exergy output (electricity and heat) and the primary exergy input as reported below:

$$\eta_{Ex,MCHP} = (\dot{E}_{x,el,MCHP,out} + \dot{E}_{x,th,MCHP}) / \dot{E}_{x,p,MCHP} \quad (15)$$

where $\dot{E}_{x,el,MCHP,out}$ is the exergy rate associated to the electrical power output, $\dot{E}_{x,th,MCHP}$ is the exergy rate associated to the transfer of heat and $\dot{E}_{x,p,MCHP}$ is the exergy fuel input rate. The values of $\dot{E}_{x,el,MCHP,out}$ and $\dot{E}_{x,p,MCHP}$ are given, respectively, by Eq. (16) and Eq. (17):

$$\dot{E}_{x,el,MCHP,out} = f_{q,el} \cdot P_{el,MCHP,out} \quad (16)$$

$$\dot{E}_{x,p,MCHP} = f_{q,fuel} \cdot \dot{m}_{fuel} \cdot LHV_{fuel} + f_{q,el} \cdot P_{el,MCHP,in} \quad (17)$$

where $f_{q,el}$ is the quality factor for the electric power and $f_{q,fuel}$ is the quality factor for fuel (natural gas): in this paper, $f_{q,el} = 1$ and $f_{q,fuel} = 1.04$ [32] are used.

Taking into account that heat is transferred from cooling water exiting the internal combustion engine to a secondary fluid in a heat exchanger, one can express the exergy rate of process heat as the exergy increase of the cold fluid in the heat exchanger by using the following formula [8]:

$$\dot{E}_{x,th,MCHP} = \dot{m}_{cw} \cdot [(h_{cw,MCHP,out} - h_{cw,MCHP,in}) - T_0 \cdot (S_{cw,MCHP,out} - S_{cw,MCHP,in})] \quad (18)$$

where $h_{cw,MCHP,out}$ and $h_{cw,MCHP,in}$ are the specific enthalpies of cooling water exiting and entering the MCHP system, respectively; $S_{cw,MCHP,out}$ and $S_{cw,MCHP,in}$ represent the specific entropies of the cooling water exiting and entering the MCHP system, respectively; T_0 is the dead-state or environment temperature.

An important issue in exergy analysis is the definition of the dead-state point, which represents conditions where the specific exergy is zero. Despite no recommended value was given in literature, the definition of the dead state conditions is a very important issue and should be chosen carefully. In this study, the outdoor temperature measured occurred during the test was assumed as reference temperature, aiming to be a result as close as possible to equilibrium between system and its boundary environment.

The specific enthalpy variation and the specific entropy variation in Eq. (18) are calculated by using the following formulas according to the measured values of cooling water temperature:

$$h_{cw,MCHP,out} - h_{cw,MCHP,in} = \bar{c}_{cw} \cdot (T_{cw,MCHP,out} - T_{cw,MCHP,in}) \quad (19)$$

$$S_{cw,MCHP,out} - S_{cw,MCHP,in} = \bar{c}_{cw} \cdot \ln(T_{cw,MCHP,out} / T_{cw,MCHP,in}) \quad (20)$$

In Fig. 7 the values of thermal power $P_{th,MCHP}$ recovered from MCHP system and primary power $P_{p,MCHP}$ consumed by the unit are compared with the exergy fuel input rate $\dot{E}_{x,p,MCHP}$ (Eq. (17)) and exergy rate of process heat $\dot{E}_{x,th,MCHP}$ (Eq. (18)).

As can be derived from Fig. 7, the difference between thermal power and exergy rate of process heat are significant: in fact $\dot{E}_{x,th,MCHP}$ is about seven times lower than $P_{th,MCHP}$. A small difference of about 4% is found between $P_{p,MCHP}$ and $\dot{E}_{x,p,MCHP}$: this is due to the quality factor of the primary energy source that we assumed equal to 1.04 [32].

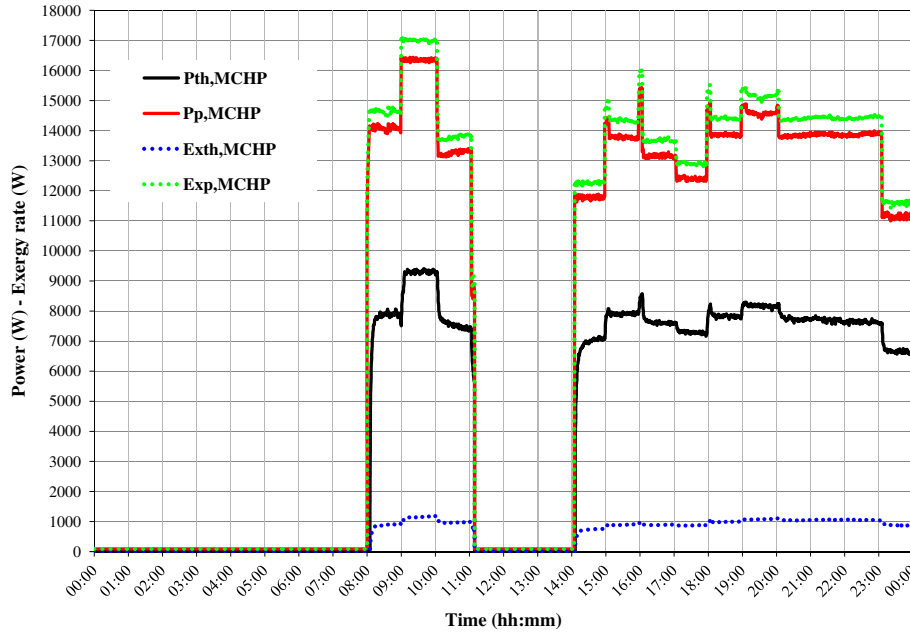


Fig. 7. Values of $P_{th,MCHP}$, $P_{p,MCHP}$, $\dot{E}x_{p,MCHP}$ and $\dot{E}x_{th,MCHP}$ as a function of the time.

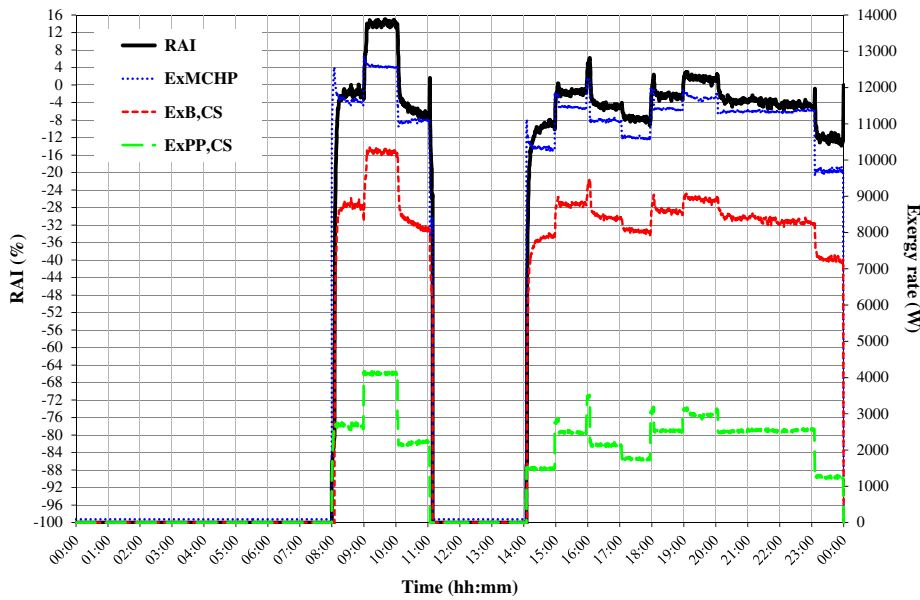


Fig. 8. Values of RAI, $\dot{E}x_{MCHP}$, $\dot{E}x_{B,CS}$ and $\dot{E}x_{PP,CS}$ as a function of the time.

An indicator for exergy analysis, named Relative Avoided Irreversibility (RAI), has been proposed in [8] with the aim to compare the irreversibilities (or exergy destruction) generated during the conversion process for the MCHP unit and the Conventional System based on separate energy production. In this paper the indicator RAI is expressed by this equation:

$$RAI = \frac{(\dot{E}x_{CS} - \dot{E}x_{MCHP})}{\dot{E}x_{MCHP}} = \frac{(\dot{E}x_{B,CS} + \dot{E}x_{PP,CS})}{(\dot{E}x_{p,MCHP} - \dot{E}x_{el,MCHP,out} - \dot{E}x_{th,MCHP})} - 1 \quad (21)$$

where the exergy loss $\dot{E}x_{B,CS}$ related to the boiler and the exergy loss $\dot{E}x_{PP,CS}$ of the Power Plant can be calculated as follows:

$$\begin{aligned} \dot{E}x_{B,CS} &= \dot{E}x_{p,B,CS} - \dot{E}x_{th,B,CS} \\ &= f_{q,fuel} \cdot P_{th,MCHP} / \eta_{B,CS} - f_{q,fuel} \cdot P_{th,MCHP} \end{aligned} \quad (22)$$

$$\begin{aligned} \dot{E}x_{PP,CS} &= \dot{E}x_{p,PP,CS} - \dot{E}x_{el,PP,CS} \\ &= f_{q,fuel} \cdot P_{el,MCHP,out} / \eta_{PP,CS} - f_{q,fuel} \cdot P_{el,MCHP,out} \end{aligned} \quad (23)$$

Eq. (23) is derived by assuming that the electric grid is fed by a natural gas fired Power Plant ($f_{q,fuel} = 1.04$).

RAI indicator can be regarded as the exergy loss that is avoided when reference plants with separate production are replaced by an actual MCHP plant: a positive value of RAI means that the case of MCHP under analysis gives a lower irreversibility than the

conventional system, i.e. cogeneration device provides an improvement with respect to the separate energy production.

Fig. 8 shows the values of RAI_E calculated by using Eq. (21) with $\eta_{PP,CS} = 0.461$ and $\eta_{B,CS} = 0.85$; the exergy rate $\dot{E}_{X_{MCHP}}$ of the MCHP system, the exergy rate $\dot{E}_{X_B}$ of the boiler and the exergy rate $\dot{E}_{X_{PP}}$ of the gas fired Power Plant are also reported on the right-hand y axis of the same figure.

As can be derived from Fig. 8, in comparison to the Conventional System, AISIN SEIKI unit allows for a reduction of the irreversibilities while the electric load assumes the highest values, i.e. from 9:00 a.m. to 10:00 a.m. and from 7:00 p.m. to 8:00 p.m.; maximum value of RAI is about 15%.

However the estimation of irreversibilities can be performed also by referring to the cumulative energies (instead of to the instantaneous values of power) as follows:

$$RAI_E = (Ex_{CS} - Ex_{MCHP}) / Ex_{MCHP} = (Ex_{B,CS} + Ex_{PP,CS}) / Ex_{MCHP} - 1 \quad (24)$$

where Ex_{MCHP} is the exergy related to MCHP system, $Ex_{B,CS}$ is the exergy related to Boiler of Conventional System, and $Ex_{PP,CS}$ is the exergy related to Power Plant of Conventional System. They can be calculated as follows:

$$Ex_{MCHP} = f_{q,fuel} \cdot E_{fuel,MCHP,in} + f_{q,el} \cdot E_{el,MCHP,in} - f_{q,el} \cdot E_{el,MCHP,out} - f_{q,fuel} \cdot E_{th,MCHP} \quad (25)$$

$$Ex_{B,CS} + Ex_{PP,CS} = f_{q,fuel} \cdot (E_{th,MCHP} / \eta_{B,CS} - E_{th,MCHP}) + f_{q,fuel} \cdot (E_{el,MCHP,out} / \eta_{PP,CS} - E_{el,MCHP,out}) \quad (26)$$

In Fig. 9 the values of RAI_E calculated by means of Eq. (24) are plotted as a function of both boiler efficiency and Power Plant efficiency, with $\eta_{PP,CS}$ ranging between 30% and 60% and $\eta_{B,CS}$ ranging from 80% to 105%. With respect to the thermal efficiency, based on LHV of the fuel, the range 85–105% has been considered in order to take into account the performance of a gas-fired condensing boiler.

Fig. 9 shows that, in the operating conditions investigated in this paper, the values of RAI_E increases with decreasing both $\eta_{PP,CS}$ and $\eta_{B,CS}$. The maximum value of RAI_E is around 22%, which is

achieved when $\eta_{PP,CS} = 30\%$ and $\eta_{B,CS} = 80\%$; the minimum value of RAI_E is around -29% , which is achieved when $\eta_{PP,CS} = 60\%$ and $\eta_{B,CS} = 105\%$. In addition it can be noticed that, when $\eta_{PP,CS}$ decreases from 60% to 30%, the increment of RAI_E is about 30% whatever is the value of $\eta_{B,CS}$; on the other hand, when $\eta_{B,CS}$ decreases from 105% to 80%, RAI_E increases about 21% whatever is the value of $\eta_{PP,CS}$. If the Power Plant efficiency is 46.1% (Italian energetic context [42]) and the boiler efficiency is 85% (average boiler efficiency) the value of RAI_E results about -3.9% : this means that Conventional System allows for a slight reduction of irreversibilities in comparison to the cogeneration unit.

6. GHG emission saving evaluation

The assessment of any pollutant emission from a combustion device can be assessed through an energy output-based emission factor approach [6]. According to this approach, the mass m_w^E of a given pollutant w emitted while producing the energy output E can be worked out as:

$$m_w^E = \mu_w^E \cdot E \quad (27)$$

where μ_w^E is the energy output-based emission factor, that is, the specific emissions of w per unit of E . This factor depends upon several operating and structural variables, such as the specific equipment, partial load operation, age, state of maintenance, outdoor conditions, pollutant abatement systems, and so forth.

Eq. (27) can be used for considering the emissions of any type of GHG for both the MCHP system and the CS. However, as far as emissions from fuel burning are concerned, in general CO_2 emissions prove to be quantitatively much more important than other GHG emissions [43]. Emissions of other important GHG such as methane, in any case, are typically comparable for MCHP system and the CS [43–45]. Therefore, at first approximation, GHG emissions other than CO_2 can be neglected. Thus, only the carbon dioxide emissions will be considered in the analyses carried out in this paper.

Chicco and Mancarella [6] introduced the novel TCO_2ER indicator for CO_2 emission reduction evaluation in MCHP systems. In this paper it is defined as follows:

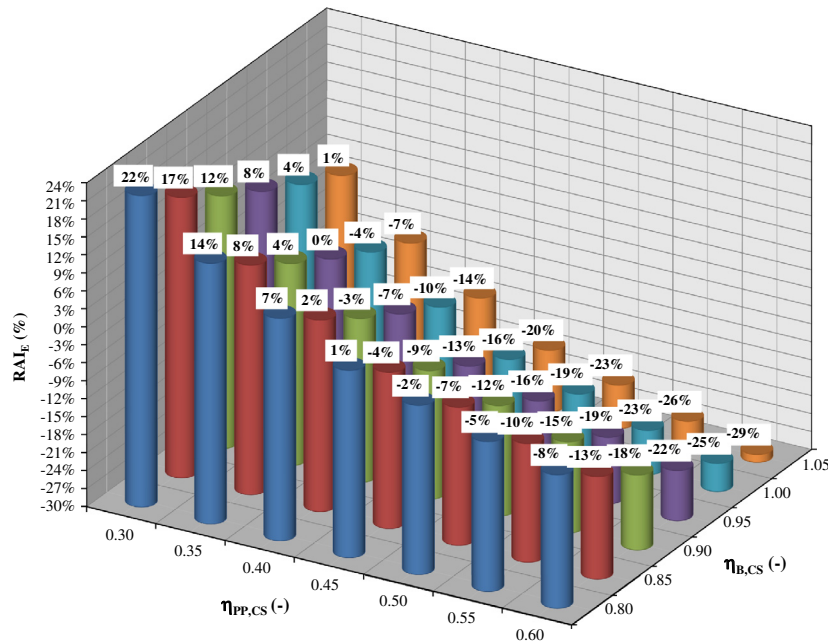


Fig. 9. Values of RAI_E as a function of $\eta_{PP,CS}$ and $\eta_{B,CS}$.

$$\begin{aligned}
\text{TCO}_2\text{ER} &= (m_{\text{CO}_2, \text{CS}} - m_{\text{CO}_2, \text{MCHP}}) / m_{\text{CO}_2, \text{MCHP}} \\
&= \left[\text{AT} \cdot (\mu_{\text{CO}_2, \text{CS}}^{\text{el}} \cdot P_{\text{el, MCHP, out}} + \mu_{\text{CO}_2, \text{CS}}^{\text{th}} \cdot P_{\text{th, MCHP}}) \right] / \left[\text{AT} \cdot (\mu_{\text{CO}_2, \text{MCHP}}^{\text{p}} \cdot \dot{m}_{\text{fuel}} \cdot \text{LHV}_{\text{fuel}} + \mu_{\text{CO}_2, \text{CS}}^{\text{el}} \cdot P_{\text{el, MCHP, in}}) \right] - 1 \\
&= \left[\text{AT} \cdot (\mu_{\text{CO}_2, \text{CS}}^{\text{el}} \cdot P_{\text{el, MCHP, out}} + \mu_{\text{CO}_2, \text{CS}}^{\text{p}} \cdot P_{\text{th, MCHP}} / \eta_{\text{B, CS}}) \right] / \left[\text{AT} \cdot (\mu_{\text{CO}_2, \text{MCHP}}^{\text{p}} \cdot \dot{m}_{\text{fuel}} \cdot \text{LHV}_{\text{fuel}} + \mu_{\text{CO}_2, \text{CS}}^{\text{el}} \cdot P_{\text{el, MCHP, in}}) \right] - 1
\end{aligned} \quad (28)$$

where $m_{\text{CO}_2, \text{MCHP}}$ is the CO_2 mass emitted while burning the fuel input to the MCHP system, $m_{\text{CO}_2, \text{CS}}$ is the CO_2 mass emitted while producing the same cogenerated energy vectors in reference CS technologies, AT is the acquisition time (equal to 30 s), $\mu_{\text{CO}_2, \text{MCHP}}^{\text{p}}$ and $\mu_{\text{CO}_2, \text{CS}}^{\text{p}}$ are the primary energy output related emission factors for the MCHP unit and the CS, respectively, $\mu_{\text{CO}_2, \text{CS}}^{\text{el}}$ and $\mu_{\text{CO}_2, \text{CS}}^{\text{th}}$ are the energy output related emission factors for the CS of electricity and heat, respectively.

TCO_2ER indicator allows for evaluating if, with respect to the Conventional System, there is potential for getting CO_2 emission reduction for the given gas-fuelled MCHP system in a given energy framework: a positive value of TCO_2ER means that the MCHP device gives lower carbon dioxide emissions than the Conventional System.

For a given fuel, the CO_2 emission factor $\mu_{\text{CO}_2, \text{MCHP}}^{\text{p}}$ referred to the primary energy released when burning the fuel can be considered constant at first approximation. In fact $\mu_{\text{CO}_2, \text{MCHP}}^{\text{p}}$ can actually change when the MCHP unit operates in generic off-design conditions. In this case, typically the combustion characteristics worsen, bringing about incomplete combustion and thus a decrease of CO_2 specific emissions [44,45]. However, this behavior can be neglected at first approximation, as done in several studies [44,46,47]. In addition, considering a constant $\mu_{\text{CO}_2, \text{MCHP}}^{\text{p}}$ is conservative for what concerns the assessment of CO_2 emission reduction brought by a combined system with respect to the CS.

A main conceptual difference between the ΔP_p and the TCO_2ER has to be pointed out. In the expression (11) of ΔP_p the specific technologies are only addressed for assessing the relevant efficiencies, but no matter the actual fuels. Differently, when evaluating the CO_2 emission performance through the TCO_2ER not only the technologies, but also the fuel inputs to the different systems are relevant. In the hypothesis that the same fuel is adopted for all the systems involved in the analysis (combined and separate generation), the TCO_2ER would assume the same numerical value of the ΔP_p .

The expression (28) allows running general parametric analyses of different types, considering different emission factors for the Conventional System. In fact, different fuels exhibit different carbon chemical contents and thus their burning would generate different CO_2 emissions [43–44]. In addition, if the CS makes reference to the power system in a given context, the actual generation mix can be based upon various alternatives. In particular, electricity production from renewable sources such as wind or sun, as well as from nuclear energy, is virtually characterized by zero CO_2 emissions. For this purpose, Table 3 reports the average

CO_2 emission factors from electricity production and natural gas consumption in different countries for the year 2003 [48].

The average CO_2 emissions depend upon the technology mix adopted for producing electricity. Thus, the emissions in Norway are significantly lower than for the other countries, as the generation system is based upon renewable sources such as hydroelectric power. Italy has a power generation system with no nuclear power and with about 20% of hydro-electricity; the main part is thermal-based, with a mix of fuels from coal to oil.

In the following it is assumed to feed the cogenerator and the reference heat generator with the same fuel (i.e. natural gas): in this hypothesis, it results that $\mu_{\text{CO}_2, \text{CS}}^{\text{p}} = \mu_{\text{CO}_2, \text{MCHP}}^{\text{p}}$.

In Fig. 10 the values of TCO_2ER indicator are plotted as a function of time based on the values of $P_{\text{p, MCHP}}$, $P_{\text{el, MCHP, out}}$ and $P_{\text{th, MCHP}}$ measured during the experimental test depicted in Section 4. Values of TCO_2ER reported in Fig. 10 have been computed with reference to average emissions from the Italian systems ($\mu_{\text{CO}_2, \text{CS}}^{\text{el}} = 525 \text{ g}_{\text{CO}_2} / \text{kW h}_{\text{el}}$ and $\mu_{\text{CO}_2, \text{CS}}^{\text{p}} = \mu_{\text{CO}_2, \text{MCHP}}^{\text{p}} = 200 \text{ g}_{\text{CO}_2} / \text{kW h}_{\text{p}}$), by assuming 0.85 as reference boiler efficiency.

It can be derived that, in the operating conditions investigated in this paper, MCHP system allows for a reduction in carbon dioxide emission ($\text{TCO}_2\text{ER} > 0$) during the most part of the experimental test duration; CO_2 emissions related to the Conventional System becomes lower than those associated to the cogeneration unit during stand-by, warm-up and cool-down operation, as well as during steady-state operation at low electric output level.

As stated above, TCO_2ER indicator is a function of the CO_2 specific emissions for electricity production and fuel consumption (depending on the country as specified in Table 1), as well as of the CS thermal efficiency. As a practical example, TCO_2ER is plotted in Fig. 11 as a function of and thermal efficiency of the reference boiler. The values reported in Fig. 11 have been calculated based on the values of energies consumed or produced by the MCHP during the experimental test ($E_{\text{gross, MCHP, out}} = 176.9 \text{ kW h}$, $E_{\text{el, MCHP, in}} = 1.0 \text{ kW h}$, $E_{\text{el, MCHP, out}} = 25.2 \text{ kW h}$, $E_{\text{th, MCHP}} = 99.9 \text{ kW h}$) specified in Section 4.

From Fig. 11, it can be derived that:

- the CO_2 emission reduction decreases with increasing the reference boiler efficiency;
- the CO_2 emission reduction increases with decreasing the percentage of electricity production coming from renewable sources;
- maximum value of TCO_2ER is about +11% (average mix of Power Plant technologies of USA, with reference boiler efficiency equal to 80%);
- minimum value of TCO_2ER is about –46% (average mix of Power Plant technologies of Norway, with reference boiler efficiency equal to 80%);
- there is a carbon dioxide reduction by using MCHP system instead of the CS ($\text{TCO}_2\text{ER} > 0$) only for two countries: USA with $\eta_{\text{B, CS}}$ lower than 0.95 and Italy with $\eta_{\text{B, CS}}$ lower than 0.87;
- the value of TCO_2ER is about +2% in case of Italian average mix of Power Plant technologies and $\eta_{\text{B, CS}} = 0.85$.

Table 3
 CO_2 specific emissions for electricity production and natural gas consumption in different countries [40].

	Italy	France	Norway	EU15	USA	Japan
$\mu_{\text{CO}_2, \text{CS}}^{\text{el}} (\text{g}_{\text{CO}_2} / \text{kW h}_{\text{el}})$	525	78	3	362	610	389
$\mu_{\text{CO}_2, \text{CS}}^{\text{p}} (\text{g}_{\text{CO}_2} / \text{kW h}_{\text{p}})$	200	203	201	203	201	202

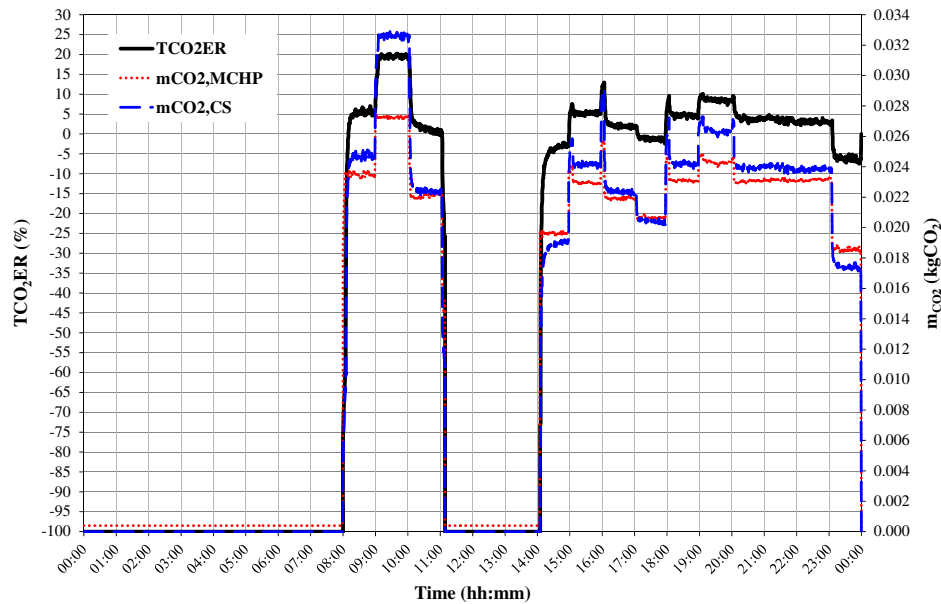


Fig. 10. Values of TCO_2ER as a function of the time.

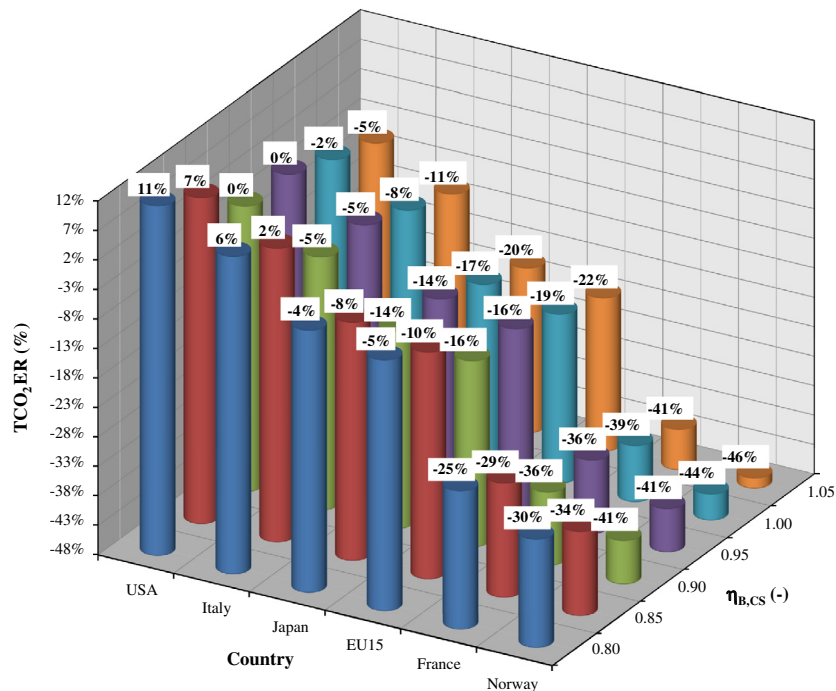


Fig. 11. Values of TCO_2ER as a function of country and $\eta_{B,CS}$.

7. Conclusions

The performance of an internal combustion engine based micro-cogeneration unit with 6.0 kW as nominal electric output has been experimentally investigated during a 24 h dynamic test. The system has been operated in electric load-following logic by applying a realistic daily electric load profile representing the Italian domestic electrical non-HVAC demand for a multi-family house of five dwellings. The performed experiment allowed taking into account the electric and thermal operation of the unit not only during steady-state operation, but also during transient periods.

The measured data have been compared with those that would be associated with servicing the building with electricity from the

central electric grid and heat from a natural gas fired boiler from an energy, exergy and environmental point of view in order to assess the suitability of the small cogeneration unit in comparison to a Conventional System based on separate energy production. The comparison has been performed by using the most meaningful indexes suggested in literature and considering various efficiency values of the reference system (from 30% to 60% for the electric grid and from 80% to 105% for the boiler).

The performed assessment showed that, in comparison to the Conventional System based on separate energy production, the MCHP unit allows reducing the carbon dioxide emissions of about 2% in case of Italian average mix of Power Plant technologies and $\eta_{B,CS} = 0.85$ (average boiler efficiency), even if it requires a slightly

higher primary energy consumption (+3.2%) and gives larger irreversibilities (+3.9%).

Taking into considerations that the utilization and wide diffusion of MCHP is strongly related to the characteristics of final users, a model of the AISIN SEIKI unit experimentally investigated in this paper has been already calibrated and validated for TRNSYS environment [34,35,49–51]. This model will be used in the future for assessing the cogeneration unit performance in comparison to the reference Conventional System under several different operating scenarios (thermal and electric demand profiles to be matched, logic of operation, etc.), also from an economic point of view.

References

- [1] Brussels European Council – 8/9 March 2007 – presidency conclusions, 2/05/2007 (English) Nr: 7224/1/07 REV1. <http://www.consilium.europa.eu/ueDocs/cms_Data/docs/pressData/en/ec/93135.pdf> [Retrieved on 09.05.12].
- [2] Directive 2004/8/EC of the European Parliament of the European Parliament and of the Council of 11 February 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market and amending Directive 92/42/EEC. Off J Eur Union; 2004.
- [3] Possidente R, Roselli C, Sasso M, Sibilio S. Experimental analysis of micro-cogeneration units based on reciprocating internal combustion engine. *Energy Build* 2006;38:1417–22.
- [4] Roselli C, Sasso M, Sibilio S, Tzscheuschler P. Experimental analysis of micro-cogenerators based on different prime movers. *Energy Build* 2011;43:796–804.
- [5] De Paeppe M, D'Herdt P, Mertens D. Micro-CHP systems for residential applications. *Energy Convers Manage* 2006;47:3435–46.
- [6] Chicco G, Mancarella P. Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part I: Models and indicators. *Energy* 2008;33:410–7.
- [7] Mancarella P, Chicco G. Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part II: Analysis techniques and application cases. *Energy* 2008;33:418–30.
- [8] Ertesvåg IS. Exergetic comparison of efficiency indicators for combined heat and power (CHP). *Energy* 2007;32:2038–50.
- [9] Bonnet S, Alaphilippe M, Stouffs P. Energy, exergy and cost analysis of a micro-cogeneration system based on an Ericsson engine. *Int J Therm Sci* 2005;44:1161–8.
- [10] Entchev E, Gusdorf J, Swinton M, Bell M, Szadkowski F, Kalbfleisch W, et al. Micro-generation technology assessment for housing technology. *Energy Build* 2004;36:925–31.
- [11] Voorspools KR, D'haeseleer WD. The evaluation of small cogeneration for residential heating. *Int J Energy Resour* 2002;26:1175–90.
- [12] Kuhn V, Klemeš J, Bulatov I. MicroCHP: overview of selected technologies, products and field test results. *Appl Therm Eng* 2008;28:2039–48.
- [13] Dorer V, Weber R, Weber A. Performance assessment of fuel cell micro-cogeneration systems for residential buildings. *Energy Build* 2005;37:1132–46.
- [14] Final Report of Annex 42 of the International Energy Agency's Energy Conservation in Buildings and Community Systems Programme. An experimental and simulation-based investigation of the performance of small-scale fuel cell and combustion-based cogeneration devices serving residential buildings; 2008.
- [15] Dorer V, Weber A. Energy and CO₂ emissions performance assessment of residential micro-cogeneration systems with dynamic whole-building simulation programs. *Energy Convers Manage* 2009;50:648–57.
- [16] Magri G, Di Perna C, Serenelli G. Analysis of electric and thermal seasonal performances of a residential microCHP Unit. *Appl Therm Eng* 2012;36:193–201.
- [17] Barelli L, Bidini G, Gallorini F, Ottaviano A. An energetic–exergetic analysis of a residential CHP system based on PEM fuel cell. *Appl Energy* 2011;88:4334–42.
- [18] Alanne K, Söderholm N, Sirén K, Beausoleil-Morrison I. Techno-economic assessment and optimization of Stirling engine micro-cogeneration systems in residential buildings. *Energy Convers Manage* 2010;51:2635–46.
- [19] Cakir U, Comakli K, Yuksel F. The role of cogeneration systems in sustainability of energy. *Energy Convers Manage* 2012;63:196–202.
- [20] Wakui T, Wada N, Yokoyama R. Feasibility study on combined use of residential SOFC cogeneration system and plug-in hybrid electric vehicle from energy-saving viewpoint. *Energy Convers Manage* 2012;60:170–9.
- [21] Angrisani G, Rosato A, Roselli C, Sasso M, Sibilio S. Experimental results of a micro-trigeneration installation. *Appl Therm Eng* 2012;38:78–90.
- [22] Pade L-L, Schröder ST. Fuel cell based micro-combined heat and power under different policy frameworks – an economic analysis. *Energy Convers Manage* 2013;66:295–303.
- [23] Watson J, Sauter R, Bahaj B, James PA, Myers L, Wing R. Unlocking the power house: policy and system change for domestic micro-generation in the UK, London, UK; 2006. <http://www.energy.soton.ac.uk/publications/unlocking_the_power_house_report.pdf>.
- [24] Hawkes AD, Leach MA. The capacity credit of micro combined heat and power. *Energy Policy* 2008;36:1457–69.
- [25] Onovwionaa HI, Ugursal VI. Residential cogeneration systems: review of the current technology. *Renew Sust Energy Rev* 2006;10:389–431.
- [26] Angrisani G, Roselli C, Sasso M. Distributed microtrigeneration systems. *Progr Energy Combust Sci* 2012;38:502–21.
- [27] <<http://www.tecno-casa.com/EN/Default.aspx?level0=prodotti&level1=mchp>> [last accessed on 09.05.12].
- [28] Sasso M, Roselli C, Sibilio S, Possidente R. Performance assessment of residential cogeneration systems in Southern Italy. A report of subtask C of FC+COGEN-SIM the simulation of building-integrated fuel cell and other cogeneration systems. Annex 42 of the International Energy Agency Energy Conservation in Buildings and Community Systems Programme; 2007.
- [29] <http://www.eerg.it/index.php?p=Progetti_-_MICENE> (last accessed on 15-05-12).
- [30] Caresana F, Brandoni C, Feliciotti P, Maria Bartolini C. Energy and economic analysis of an ICE-based variable speed-operated micro-cogenerator. *Appl Energy* 2011;88:659–71.
- [31] Vio M. Impianti di cogenerazione. 1st ed. Milano, Italy: Editoriale Delfino; 2006.
- [32] Kotas TJ. The exergy method in thermal plant analysis. 2nd ed. Malabar: Krieger; 1995.
- [33] Bejan A. Advanced engineering thermodynamics, third ed. New Jersey: John Wiley and Sons, Inc., Hoboken; 2006.
- [34] Rosato A, Sibilio S. Calibration and validation of a model for simulating thermal and electric performance of an internal combustion engine-based micro-cogeneration device. *Appl Therm Eng* 2012;45–46:79–98.
- [35] Rosato A, Sibilio S. Energy performance of a micro-cogeneration device during transient and steady-state operation: experiments and simulations. *Appl Therm Eng* 2013;52:478–91.
- [36] UNI CEI ENV 13005:2000 Guide to the Expression of Uncertainty in Measurement (GUM).
- [37] ISO 12213-2:2006. Natural gas – calculation of compression factor – Part 2: Calculation using molar-composition analysis.
- [38] Dentice d'Accadia M, Musto M. Engineering analysis of uncertainties in the performance evaluation of CHP systems. *Appl Energy* 2011;88:4927–35.
- [39] Carotenuto A, Giovinco G, Viglietti B, Vanoli L. A new procedure for the determination of calibration curves for a gas chromatograph used in natural gas analysis. *Chromatogr Intell Lab Syst* 2005;75:209–17.
- [40] Cascetta F, Musto M, Rotondo G. Measurement of the compressed natural gas in automotive application: a comparative analysis between mass vs. volumetric metering methods. *Flow Measure Instrum* 2008;6:338–41.
- [41] Rossi N. Manuale del Termotecnico, second ed. HOEPLI; 2007.
- [42] Italian Electricity and Gas Authority website (Autorità per l'energia elettrica e il gas). <www.autorita.energia.it> [last accessed on 15.05.12].
- [43] Danny Harvey LD. A handbook on low-energy buildings and district energy systems: fundamentals, techniques, and examples. UK: James and James; 2006.
- [44] EDUCOGEN, The European Educational Tool on Cogeneration; 2001. <www.cogen.org/projects/educogen.htm> [last accessed on 15.05.12].
- [45] Distributed Energy Resources Emissions Survey and Technology Characterization, E21, Palo Alto, CA, Ameren, St. Louis, MO, California Energy Commission, Sacramento, CA, New York Independent System Operator, Albany, NY, and New York Power Authority, White Plains, NY, <<http://www.eprweb.com/public/000000000001011256.pdf>> [last accessed on 15.05.12].
- [46] Meunier F. Co- and tri-generation contribution to climate change control. *Appl Therm Eng* 2002;22:703–18.
- [47] Cărdău M, Baica M. Regarding the greenhouse gas emissions of thermopower plants. *Energy Convers Manage* 2002;43:2135–44.
- [48] Intergovernmental Panel on Climate Change, Working Group III. Data on carbon dioxide intensities. <http://arch.rivm.nl/env/int/ipcc/pages_media/SROC-final/Tables/t0305.pdf> [last accessed on 15.05.12].
- [49] Solar Energy Laboratory. TRNSYS 16, A transient system simulation program, Tech. rep. Madison (USA): University of Wisconsin; 2004.
- [50] Ferguson A, Kelly N, Weber A, Griffith B. Modelling residential-scale combustion-based cogeneration in building simulation. *J Build Perform Simul* 2009;2:1–14.
- [51] Kelly N, Beausoleil-Morrison I. Specifications for modelling fuel cell and combustion-based residential cogeneration devices within whole-building simulation programs. IEA/ECBCS Annex 42 report; 2007.